

# Comparisons and Combinations of Oscillation Measurements

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## 1 Introduction

For a three active neutrino scenario, neutrino oscillations are described by six physics parameters:  $\theta_{13}, \theta_{12}, \theta_{23}, \Delta m_{12}^2, \Delta m_{23}^2$ , and the CP violation phase,  $\delta$ . In addition, a full description also requires knowing the hierarchy of mass state 3 relative to 1 and 2, *i.e.* the sign of  $\Delta m_{23}^2$ . Of the six parameters, it is assumed for this study that  $\theta_{12}, \theta_{23}, \Delta m_{12}^2$ , and  $\Delta m_{23}^2$  are known to the precision expected from either the current program (SuperK, Minos and CNGS) or the future program (Nova and T2K). This leaves for determination  $\theta_{13}, \delta$ , and the mass hierarchy which are the subject of this study. Table 1 lists the values as well as the current and future errors used in the study for  $\theta_{12}, \theta_{23}, \Delta m_{12}^2$ , and  $\Delta m_{23}^2$ .

The experimental inputs for the study are given in Table 2 and are derived from estimates of the measurement sensitivities. Three reactor experiments are considered corresponding to a small (Double-CHOOZ), medium(Braidwood, Daya Bay type), or large (MiniBooNE size) reactor  $\bar{\nu}_e$  measurement. Two offaxis long-baseline experiments are considered, JParc to SuperK (T2K) and the NuMI offaxis proposal (Nova). The sensitivities for the reactor experiments are scaled from the  $\sin^2 2\theta_{13}$  90% C.L. limits at  $\Delta m_{23}^2 = 2.5 \times 10^{-3} \text{ eV}^2$  for a null oscillation scenario. For the long-baseline experiments, the uncertainties are scaled from the expected number of events given in the Nova proposal and a recent talk by Y. Suzuki at the Seesaw workshop. The given uncertainties include statistical errors associated with the background and signal for a 5 year data run but no systematic uncertainty.

The uncertainty on the  $\theta_{23}$  parameter can have a significant effect on the long-baseline measurements since the quantity that is constrained as given in Table 1 is  $\sin^2 2\theta_{23}$  and the parameter that modulates the long-baseline oscillation probability is  $\sin^2 \theta_{23}$ . This can lead to a 65% (23%)

| Parameter                      | Value                | Current $\sigma$               | Future $\sigma$             |
|--------------------------------|----------------------|--------------------------------|-----------------------------|
| $\sin^2 2\theta_{23}$          | 1.0                  | 0.06 (SuperK)                  | 0.01 (T2K)                  |
| $\Delta m_{23}^2(\text{eV}^2)$ | $2.5 \times 10^{-3}$ | $0.33 \times 10^{-3}$ (SuperK) | $0.05 \times 10^{-3}$ (T2K) |
| $\theta_{12}(\text{deg})$      | 30                   | —                              | —                           |
| $\Delta m_{12}^2(\text{eV}^2)$ | $7.1 \times 10^{-5}$ | —                              | —                           |

Table 1: Current and future uncertainty estimates on oscillation parameters. This study assumes values corresponding to the future estimates.

| Experiment                   | Basis of Estimate   | Osc. Prob. and $\sigma$ for $\sin^2 2\theta_{13} =$ |                   |                   |
|------------------------------|---|---|-------------------|-------------------|
|                              |   | 0.02  | 0.05              | 0.10              |
| Reactor ( $E_\nu = 3.6$ MeV) | $\sin^2 2\theta_{13}^{Limit}$   |   |                   |                   |
| $\langle L \rangle$          | @ $\Delta m_{23}^2 = 2.5 \times 10^{-3} \text{eV}^2$                  |   |                   |                   |
| Small 1.05 km                | 0.03@90%CL  | $0.013 \pm 0.018$                                   | $0.032 \pm 0.018$ | $0.064 \pm 0.018$ |
| Medium 1.8 km                | 0.01@90%CL  | $0.020 \pm 0.006$                                   | $0.050 \pm 0.006$ | $0.100 \pm 0.006$ |
| Large 1.8 km                 | 0.005@90%CL   | $0.020 \pm 0.003$                                   | $0.050 \pm 0.003$ | $0.100 \pm 0.003$ |
| T2K ( $E_\nu = 600$ MeV)     | $N_{events}^{5yrs}$ : $\sin^2 2\theta_{13} = 0.1$ , $\delta_{CP} = 0$ |   |                   |                   |
| $\langle L \rangle = 295$ km | @ $\Delta m_{23}^2 = 2.5 \times 10^{-3} \text{eV}^2$                  |   |                   |                   |
| $\nu$                        | 102 signal / 24.9 bkgnd   | $0.011 \pm 0.003$                                   | $0.026 \pm 0.004$ | $0.051 \pm 0.005$ |
| $\bar{\nu}$                  | 38.5 signal / 14.4 bkgnd  | $0.009 \pm 0.006$                                   | $0.022 \pm 0.007$ | $0.044 \pm 0.009$ |
| Nova ( $E_\nu = 2.3$ GeV)    | $N_{events}^{5yrs}$ : $\sin^2 2\theta_{13} = 0.1$ , $\delta_{CP} = 0$ |   |                   |                   |
| $\langle L \rangle = 810$ km | @ $\Delta m_{23}^2 = 2.5 \times 10^{-3} \text{eV}^2$                  |   |                   |                   |
| $\nu$                        | 175.2 signal / 38.1 bkgnd   | $0.011 \pm 0.002$                                   | $0.025 \pm 0.003$ | $0.048 \pm 0.003$ |
| $\bar{\nu}$                  | 66 signal / 22 bkgnd  | $0.008 \pm 0.003$                                   | $0.018 \pm 0.004$ | $0.034 \pm 0.005$ |

Table 2: Estimates of the experimental uncertainties associated with various future oscillation experiments. For the long-baseline experiments, the given uncertainties include statistical errors associated with the background and signal for a 5 year data run but no systematic uncertainty.

uncertainty in the oscillation probability with the present (future) errors.

For the studies given below, the uncertainties due to the variations of  $\theta_{23}$ ,  $\Delta m_{23}^2$ , and the mass hierarchy are included. For  $\bar{\nu}$  running, there can be up to a 20% contamination of  $\nu$  oscillation events within the analysis cuts; for the studies presented here, this contamination is assumed to be zero. Results are typically given for five year data runs but in addition some results are presented for  $\times 5$  the nominal rate (or 25 effective years) which would somewhat correspond to an upgraded long-baseline program with a new proton driver at Fermilab or the Hyper-K upgrade at JParc.